Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia CIRP 1 (2012) 325 – 329
www.elsevier.com/locate/procedia

5th CIRP Conference on High Performance Cutting 2012

Highly integrated piezo-hydraulic feed axis

J. Fleischer[a], J.Bauer[a,]*

[a]wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
* Corresponding author. Tel.: +49-721-608-46019; fax: +49-721-608-45005.E-mail address: joerg.bauer@kit.edu.

Abstract

Currently used micro-machines are mostly based on macro machine tool principles. This leads to an unfavorable ratio of build and work space and also to high moving masses in comparison to the workpiece mass. To address these disadvantages it is necessary to develop new approaches for micro machines, micro machine components and new kinematic chains especially adapted to the requirements of micromachining. Therefore a new feed unit is designed featuring a highly integrated piezo-hydraulic feed axis, a parallel kinematic and a millimeter based radar measurement system. In this paper the design approach and the characterization of the compact highly integrated piezo-hydraulic feed axis is presented.

Keywords: Micromachining; Conceptual design; Hydraulic;

1. Introduction

The high-tech strategy of the German Federal Ministry of Education and Research identifies micro system technology as the key technology of the next years. The fields of application of micro technology, i.e. medical engineering, optical systems and increasingly, automotive engineering, give rise to hopes for high revenue and growth rates [1]. Production engineering is faced with even more demanding challenges, such as an increase in complexity, miniaturization, and the functional integration of micro components. Today's research activities in contrast often focus on expanding and modifying existing manufacturing methods and combining them to form complex manufacturing chains.

Machine tools used to machine small parts offer additional potential for optimization. Such parts can be defined as parts with overall dimensions smaller than 10 x 10 x 5 cm³. They feature structures in mm and µm as well as a tolerance in the µm and sub-µm range. The areas of application of such parts are precision engineering and micro technology [2]. The machines, e.g. used for chip removing were often developed from machines used in macro machining, and therefore often consist of known kinematic units and tried and tested components [3], [4] and [5]. As a result, the floor space required for a micro milling machine with a Tool Center Point (TCP) positioning error smaller than 2 µm is approximately one square meter [6]. As a result, the machines do not only have an unfavorable ratio of build space and work space, but also of moving machine mass and workpiece mass.

2. State of the art

2.1. Micro Machine Tools

Compared to a potential work piece, e.g. a common micro mold for injection molding with an area of 50 x 30 mm², the ratio between build space and work space of today's machine tools is unfavorable [3], [6]. In addition to that, the ratio between the high moving masses of the used components and the work piece mass of the micro components that are machined is highly disproportionate. In addition to higher resource consumption for the production of the machine components it requires a significantly increased energy input to run the machine compared to the input needed for micromachining. Acceleration and long traverse paths in particular require the high power inputs that lead to the high energy consumption [3].

 http://dx.doi.org/10.1016/j.procir.2012.04.058

Components that require high driving power emit heat which heats up the machine. As a result, the accuracy can suffer because of thermal expansion. Also, the fact that today's components are combined with known kinematic chains can lead to problems in particular for five-axis machining [3]. In some configurations components collide, e.g. a feed axis and a work piece clamping device. Clash conditions are defined to avoid this problem. However, this may makes it impossible to set some of the axis positions required for a specific contour. These restrictions limit the work space and the component complexity of the micro parts that is achievable with the machine [3].

The bottom line is that the growth experienced by micro system technology has increased the demand for machine tools that are suitable for micro production. Today's machine tools do not offer an optimal ratio between build space and work space as well as the ratio of moving masses to workpiece masses. Therefore it is essential to develop new machine concepts and components based on innovative approaches facilitating adaptable machine tools especially designed for micromachining. Possible approaches to overcome the above-described ecological, technical and economic issues of currently used machines are miniaturization, increasing functional integration, implementing new drive principles and using new kinematic chains [3].

2.2. Requirements for a small machine tool

Three main targets can be defined for the micro machine. The machine tool must be compact, precise and highly dynamic. 'Compact' means that the maximum build space for a work space of 30 x 50 x 10 mm^3 is 300 x 300 x 300 mm^3 and should not be exceeded. For the functional prototype, a positioning error of ± 1 µm is targeted for the TCP. This work space and this positioning error are general sufficient for micromachining, e.g. for the production of mold inserts for micro injection molding. To manufacture small parts with high precision and quality it is additionally required to have a high level of running smoothness, a kinematic unit with no backlash and the highest possible damping of the guiding device. The target indicators for the feed unit's dynamics are 10 m/s^2 and a feed rate of 3500 mm/min. This corresponds to the values that are common for micro milling machines today. The machine tool must provide a cutting power of 20 N at the TCP. This is generally sufficient for milling cutters with a diameter of 50 µm, and the cutting rates and chip widths [7], [8] that are commonly used in micromachining.

3. Approach

3.1. Overall concept of the feed unit

The in this article presented feed axis is one part of a feed unit specifically geared towards the use in the micro range. The feed unit consists of two feed axes aligned in parallel that are linked to the TCP using a parallel kinematic unit with flexure hinges (Fig. 1). The positions of the feed axes and of the TCP will be identified through the use of measurement systems based on radar millimeter-wave sensors.

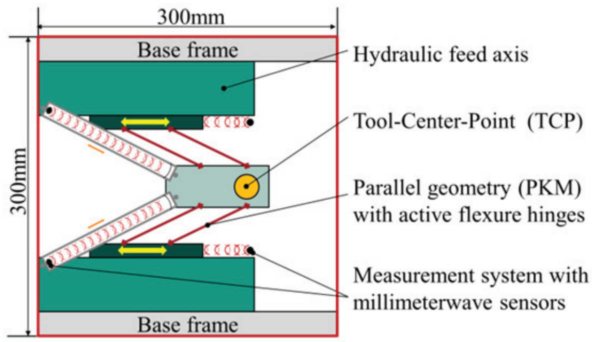

Figure 1: Overall concept feed unit

A two-stage process is used for the exact positioning of the TCP. First, the TCP is roughly positioned via the flexure hinges, i.e. the struts of the parallel kinematic unit, using the two external feed axes. Piezo-electric actuators on the flexure hinges are used to deform them actively in the micro meter range to adjust TCP to its final precision. The TCP is positioned accurately performing these two steps. Below, the functionally highly integrated feed axis is described in more detail.

3.2. Requirements and target for the feed axis

The following requirements for the feed axis can be established based on the three sub-targets:

The feed axis must be functionally highly integrated and must have a high power density. For the high precision target to be achieved axis stiffness must be equally in both axial directions. The guides must be stick-slip free and feature good damping. For the target of high dynamics to be met, integrated and highly dynamic control elements must be used, and the moving masses must be small.

Combining the high power density of a hydraulic synchronizing cylinder with small moving masses and the multifunctional use of oil for cooling and for hydrostatic guides is a highly promising approach.

Therefore, the objective is to develop a highly integrated, hydraulic feed axis that is controlled by piezo seat valves. Additional targets for the hydraulic feed axis can be established based on the requirements for the feed unit and the parallel kinematic unit. A feed rate of more than 3500 mm/min and a traverse path of ± 35 mm are targeted. As axial force 5000 N are aimed for the deformation of the flexure hinges.

4. Results

4.1. Compact hydraulic feed axis

The demand for equal stiffness in both axial directions requires the piston surface areas in both piston chambers to be of the same size. This is why a synchronizing cylinder is used. The demand for high stiffness, in particular in standstill, further leads to the requirement that the pressure in both piston chambers must be the same especially during standstill. The seal gap between the piston rod and the piston housing leads to a continuous leak of oil. Therefore, oil must be continuously supplied in order to maintain the pressure. This is why the control valves are integrated into the return flow of the actuator, similar to the principle of exhaust air throttling used in pneumatics. This way, the required oil is supplied whenever required, thus keeping the piston in position from both sides.

The leak oil flow caused by the gaps is accepted because it helps reducing friction and thus stick-slip effects resulting from friction. Furthermore, the oil flow serves for cooling and for cylinder venting.

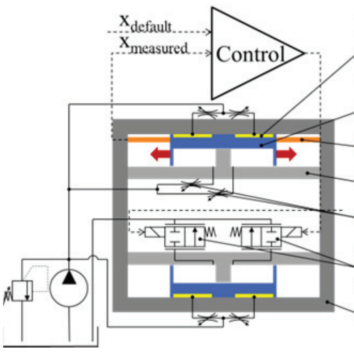

Figure 2: Concept for the piezo-hydraulic feed axis

The control principle can be characterized as a two metering edges control. Adjustable throttles have been integrated into both supply apertures to ensure that an opening of the valve does not lead to an uncontrolled flow of fluid into the piston chamber (Fig. 2).

The moving masses must be reduced in order to allow high dynamics. Therefore, the developed concept features the smallest possible moving masses. This was made possible by having a stationary actuator housing and piston rod. The piston housing is the only moving part comprising the guidance system and the carriage. The fixed oil columns must be reduced in order to increase the control dynamics of the feed axis. Therefore, the two piezoelectric proportional seat valves must be integrated directly into the stationary piston rod (Fig. 2 and Fig. 3). The piston housing that is moving in a linear direction has been integrated into a hydrostatic guide to achieve the required high level of damping. Through systematic combination of potential cylinder and guide concepts the concept illustrated in Fig. 3 was derived by comparing the respective build spaces of the different options. This is the concept with the highest compactness.

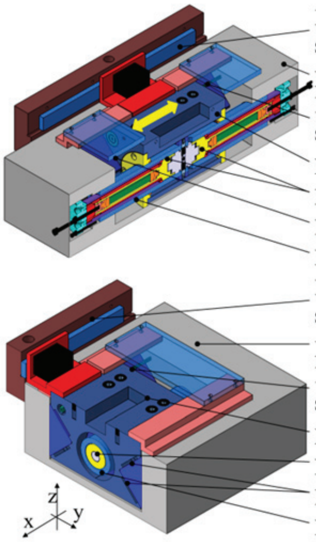

Figure 3: (a) Longitudinal cut and (b) cross-section of the feed axis's concept

The hydrostatic guide similar to [8], [9], is attached to the exterior of the piston housing. It is resting on two prisms located on the external housing. Two pressure pockets have been integrated into each top and bottom side of the prisms (making for a total of 8). The pressure pockets are supplied with pressure via constant throttles. All gaskets experiencing relative movements, e.g. those between piston housing and prisms, are restrictive seals. This helps preventing all friction-induced effects. The radar measurement system will be used to control the feed axis.

For the functional prototype, a glass scale is additionally used. It will be provisionally used to control the system, but serves also as a reference measurement system to characterize the radar measurement system.

Fig. 4 shows the implemented functional prototype. It was designed using the guideline VDI 2206 [11] and Catia V5 R20 comprising the design as well as FEM analysis. The prototype is realized with the use of standard components like the piston bushing, the control valves and prisms. It is implemented to characterize the dynamic and static behavior of the concept as well as of the hydraulic settings.

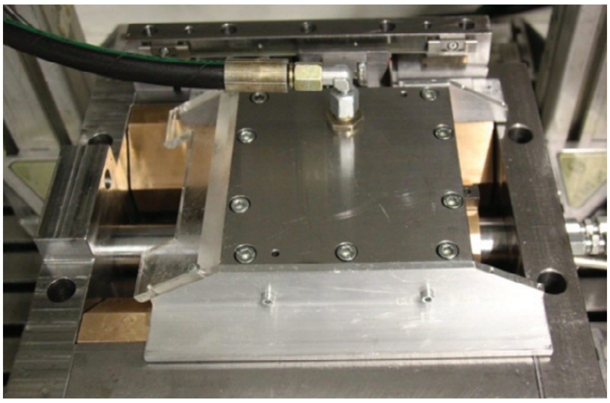

Figure 4: Prototypic realization of the feed axis

The carobronze prisms attached to each side can be adjusted with shims and allow the defined setting of the oil gap of the hydrostatic guide. The gap width of the functional prototype's hydrostatic guidance system is approximately 20 µm. The piston moves up and down in a honed piston tube. Supply and return are facilitated via the trepanned, fixed piston rod. Currently, the external dimensions of the prototype are 350 x 245 x 105 mm³. The dimensions result from the fact that the prototype is built from standard parts. By building the system without standard parts the dimensions can be decreased significantly. Currently, the feed axis is driven with a pressure of 10 MPa. The pressure is reduced to 2 MPa for the hydrostatic guide. The traverse path of the feed axis is ±35 mm.

4.2. Characterization of the prototypic implemented feed axis

The first step to characterize the functional prototype of the feed axis is the determination of its stiffness in x- as well in z-direction. The stiffness in x- and z- direction is measured comprising a pneumatic cylinder with a piezoelectric load cell and a dial gauge (accuracy of measurement 1 µm) for displacement measurement. The feed axis stiffness in z-direction is presented in Fig. 5. The stiffness depends on the forces applied in z-direction (two measurements with 1.000 N and 2.000 N). Also it decreases with increasing pressures of the hydrostatic guidance system due to elastic deformation of the feed axis's housing resulting in wider oil gaps. The hydrostatic guidance system features its maximum stiffness at 2 MPa and an applied force of 2.000 N.

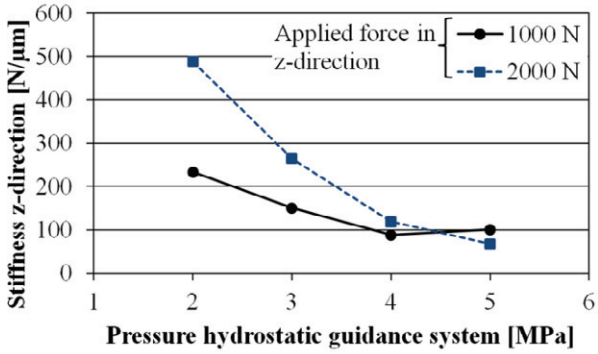

Figure 5: Stiffness in z-direction at different pressures

With active gap control, e.g. with progressive volume flow controllers, it should be possible to increase the stiffness in the specified direction. The feed axis features axial stiffness around 70 N/µm measured at 10 MPa. It can be stated that due to different states of the control valves as well as the throttles stiffness varies. The highest stiffness can be measured with one valve closed. This set can be compared to an ordinary cylinder with pressure applied on one side. The axial stiffness should increase with higher pressures.

If friction based effects, like the stick-slip effect, would appear, they are expected to appear especially at low velocities. They arise in vibrations leading to forward and backward moving of the carriage. This should present itself in peaks and an agitated characteristic in the stroke measurement. For the analysis, the feed axis was moved at low speeds while measuring speed and stroke as a function of time. The measurement at a velocity of 5 mm/s is shown in Fig.6.

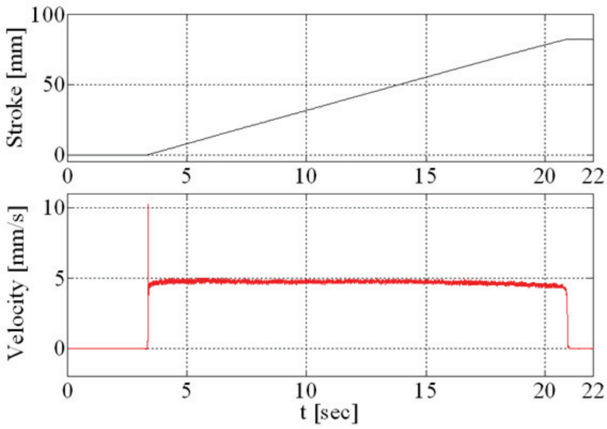

Figure 6: Investigation of friction based effects

The measurement was conducted with a DSpace System at a sampling rate of 1000 Hz. The stroke was measured with an incremental glass scale featuring a resolution of 0.4 µm. The speed was obtained by mathematically deriving the stroke's signal. The measurement uncertainty can be calculated by the measurement system's resolution and the sampling rate. It measures 0.4 mm/s. The smooth characteristic with no peaks of the stroke especially at the beginning of the movement leads to the conclusion that the axis features no friction based effects like the stick-slip effect. The abrupt stop is due to the stroke boundaries. The feed axis features a maximum velocity of 10.000 mm/min and an acceleration of 10 m/s².

5. Conclusion

The hydraulic feed axis presented in this article combines a hydrostatic guide with a hydraulic actuator. According to the main target accuracy it features no stick-slip effects, high running smoothness and the highest possible damping of all guidance systems, due to a hydrostatic guidance system. As well it features high compactness due to the high power density of hydraulics. The presented concept of the feed axis allows creating a machine tool within the specified build space. The axis features a velocity of 10.000 mm/min and a maximum acceleration of 10 m/s² as specified in the requirements.

In the next steps the stiffness and the dynamic behavior with active control will be investigated. Furthermore a coupled simulation model for hydraulics, mechanics and piezo electrics using Matlab/Simulink will be developed. Based on the results, strategies for further optimization of the feed axis especially the build space will be derived.

Acknowledgements

This paper is based on investigations of the collaborative research program SPP1476 which is kindly supported by the German Research Foundation (DFG).

References

[1] Referat Mikrosystemtechnik, Integrierte Intelligenz - Perspektiven der Mikrosystemtechnik 2010, Berlin: Bundesministerium für Bildung und Forschung, Hightech-Strategie; 2010.
[2] Schubert A, Neugebauer R, Schulz B. System Concept and Innovative Component Design for Ultra-Precision Assembly Processes. Bundesministerium für Bildung und Forschung, Hightech-Strategie; 2010. Towards synthesis of micro-/nano-systems. 11th International Conference on Precision Engineering, ICPE 2006 : August 16 - 18, 2006, Tokyo, Japan, London: Springer, 2007. DOI: 10.1007/1-84628-559-3_4
[3] Wulfsberg JP, Redlich T, Kohrs P. Square Foot Manufacturing: a new production concept for micro Manufacturing. Production Engineering, Vol. 4, Number 1/February 2010, Berlin: Springer Verlag; 2010, pp. 75-87.
[4] Dornfeld D, Min S, Takeuchi Y. Recent advances in mechanical micromanufacturing. CIRP-Annals Vol. 55; 2006, pp. 745–768.
[5] Wulfsberg JP, Grimske S, Kohrs P, Kong N. Kleine Werkzeugmaschinen für kleine Werkstücke - Zielstellungen und Vorgehensweise des DFG-Schwerpunktprogramms 1476. wt Werkstattechnik online Vol 11/12-2010; 2010, pp. 886-891.
[6] Beuthner A. Fräsen High-Speed-Fräsen im Mikrometerbereich. wt Werkstattstechnik online, Vol. 7/8-2009; 2009 pp. 516-517.
[7] Kotschenreuther J. Empirische Erweiterung von Modellen der Makrozerspanung auf den Bereich der Mikrobearbeitung. Forschungsberichte aus dem wbk Institut für Produktionstechnik Universität Karlsruhe (TH), Vol. 141, Aachen: Shaker Verlag; 2008.
[8] Lanza G, Fleischer J, Kotschenreuther J, Peters J, Schlipf M. Statistical modelling of process parameters in micro cutting. Journal of Engineering Manufacture Part B, Vol. 222 Nr. 1; 2007, pp. 15-22.
[9] Fleischer J, Knödel A, Munzinger C, Active hydrostatic guiding system with adaptronical Sensor/Actuator Unit. Conference contribution, 5th International Fluid Power Conference, Aachen; Aachen; 2006.
[10] Munzinger C, Weis M, Herder S. Adaptronic hydrostatic guiding system for intelligent level control of machine tool slides. 12th International Adaptronic Congress 20-21 May 2008, Berlin; Berlin; 2008.
[11] VDI guideline 2206. Design methodology for mechatronic systems. Verein Deutscher Ingenieure, Düsseldorf 2004.